Particle Energization in Relativistic Electron-Positron Pair Plasmas in Astrophysics

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Relativistic electron-positron pair plasmas are ubiquitous in astrophysics. Understanding the energy conversion in such plasmas is important when interpreting observations of neutron stars, gamma-ray bursts, and relativistic jets from supermassive black holes. We present large-scale 3D particle-in-cell simulations to examine particle energization in the magnetic reconnection of relativistic electron-positron (pair) plasmas. These simulations are large enough to accommodate a sufficient number of different types of instabilities. We find that particles are mostly energized inside the magnetic islands during the tearing instability stage due to the spatially varying electric fields produced by the outflows from reconnection.

Relativistic plasmas are ubiquitous in nature. The Crab Nebula is radiating radio waves to TeV gamma rays, energized by a central rapidly spinning neutron star that spills out relativistic electron-positron (pair) plasma winds. Similarly, highly relativistic jets are observed to emanate from spinning supermassive black holes—many believe such jets could be composed of relativistic pair plasmas. How to utilize the magnetic energy in the powerful jets and outflows to efficiently accelerate electron-positron pairs to extremely high energies (with Lorentz g beyond 10^7) in such highly relativistic systems is a unique challenge in plasma astrophysics. The vast scale separation between the putative scale that characterizes the dynamic motion of relativistic particles and the observed scale that jets and outflows exhibit has challenged the most powerful computing resources to date.

Magnetic reconnection, a basic plasma process that allows the magnetic fields to “reconnect” and dissipate their energy to plasmas, has been proposed as a possible route for accelerating pairs to relativistically high energies. The past decade has seen a steady growth in understanding the reconnection processes via laboratory experiments, spacecraft observations in the Earth’s magnetosphere and the solar wind, and some of the heroic computer simulations on Roadrunner [1].

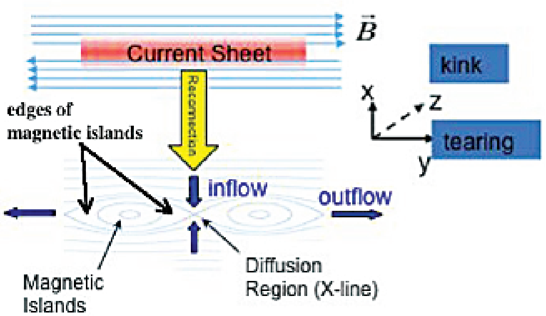

Fig. 1. Overall geometry of the simulation. Initially there is an anti-parallel magnetic field (cyan arrows) in the x-y plane and a current sheet (pink) in the z direction at the interface. After an initial perturbation from thermal noise, magnetic reconnection in the x-y plane would take place. Inflow (blue vertical arrows), outflow (blue horizontal arrows), and magnetic islands would form. In the z direction, the strong current could induce current-driven instabilities such as kink instability. Edges of magnetic islands are indicated by the black arrows. Two main types of instabilities are excited in this configuration: the tearing instability along the y direction and the kink instability along the z direction.

The study of magnetic reconnection in relativistic pair plasmas is still relatively new and has its unique advantages. The equal mass between a positron and an electron eases the computing demand of following two very different species in the ordinary proton-electron plasmas. In this study, in order to get direct information on the dynamic behavior of relativistic particles, we have used the powerful particle-in-cell code VPIC [2] to investigate, from first principles, the dynamic interaction between magnetic fields and relativistic pairs. Previous reconnection studies of relativistic pair plasmas have focused on the fast reconnection and particle acceleration mostly in 2D, or reconnection onset in 3D with a relatively small system size. It has been shown that instabilities in a cross-field plane, such as the Kelvin-Helmholtz instability (KHI) and the drift kink instability (DKI), are of critical importance to understanding magnetic energy dissipation. The relatively small sizes in previous simulations raised the intriguing question of how the evolution will change in a truly 3D configuration.

In this study, we present a numerical study of 3D magnetic reconnection of relativistic pair plasma with an emphasis on particle energization [3]. Figure 1 illustrates the simulation geometry, showing the initial magnetic field and current configurations and the expected evolution driven by both the relativistic tearing and kink instabilities. The initial pair plasma temperature is $m_e c^2$, where m_e is the mass of electron and c is the speed of light. Both species have relativistic Maxwellian distributions. In such anti-parallel geometry, the linear Vlasov theory predicts two types of instabilities: tearing, with wave vectors along y, and kink, along z. Careful analysis of the early stages of our nonlinear simulations yields near-perfect agreement between the simulation and the linear Vlasov theory. To examine how the reconnection dynamics may be influenced by both the linear and nonlinear competition between the tearing instability (in the x-y plane) and the kink instability (in the x-z plane), we use four simulations with the same size in the tearing plane $L_x = L_y = 200\ d_i$ but with different sizes in L_z, ranging from 1 to 200 d_i (where di is the positron inertial length), so that different spectra of kink modes can be excited. These simulations are some of the largest to date.

Figure 2 shows the global evolution of magnetic fields and their associated current structures from three runs with L_z =20, 50, and

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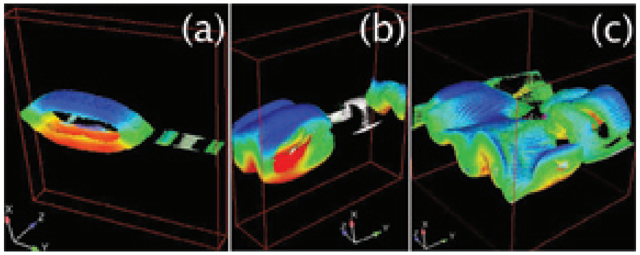

Fig. 2. Global evolution of reconnection from three different simulations. The blue-red regions are isosurfaces of pair plasma density with color indicating peak of By; embedded are the pink-white regions for the isosurfaces of |B| with color indicating peak of |J|. As the tearing instability develops into the nonlinear stage, it produces a large-scale magnetic island and reconnection site. As the simulation box gets larger in the z-direction (panels a, b, c correspond to L_z=20, 50, and 200 d_i), the development of the kink instability in the z-direction becomes important, causing the current sheet to warp.

200 d_i. Because the tearing instability emerges first due to its higher growth rate, it prompts the formation of magnetic islands and reconnection "X-lines." Magnetic field topology undergoes significant changes at these X-lines and islands, which typically go through three stages: (1) the linear instability produces a series of magnetic islands and reconnection sites, (2) these small islands coalesce to produce a dominant reconnection site (along with a main island) through which most of the magnetic flux is processed, and (3) the current sheet along the z-direction is bent by the secondary kink instability and forms plasmoids. When the z-dimension is not large enough (Fig. 2a), however, the evolution and saturation is predominantly governed by the tearing instability alone. But when the z-dimension is large enough, the kink instability causes the current sheet along the z-direction to warp, resulting in a truly 3D picture (Fig. 2b and 2c). This difference emphasizes the importance of having a sufficiently large simulation box in the z-dimension so that the full sets of instabilities can be captured.

While these instabilities are fully developing, tearing up, and warping the current sheets, what happens to the particles? Figure 3 shows the particle energy distributions at different evolution stages based on two runs, one run with $L_z = d_i$ (panels a, b, and d) and the other with $L_z = 50$ d_i (panel c). Panels a and c represent the particle energy distribution from the whole computational domain of these two runs. Panels b and d represent the particle distribution taken from a sampling box with $\delta x = \delta y = 2d_i$ at the magnetic island (b) and the reconnection site (d) of the first run. The four curves in each panel represent four characteristic stages of the evolution: (1) initial state, (2) end of the linear phase, (3) end of the nonlinear interaction stage, and (4) during the secondary kink.

The surprising result is that the particle acceleration is small at the reconnection site, as indicated in panel d, first by the blue curve (showing acceleration), followed by the green and red curves (showing decrease in energy). The main energization is actually happening at the magnetic island, as indicated in panel c by the blue, green, and red curves progressively. More detailed analysis reveals that both the volume and number of particles that experience the reconnection electric fields in islands are much larger than those in reconnection sites. To understand the details of particle energization, we have analyzed the spatial distribution of E^2–B^2, where E and B are the electric and magnetic fields, respectively. The reconnection regions indeed have E^2–$B^2 > 0$, indicating the existence of a net electric field that can accelerate particles. Most other regions have E^2–$B^2 < 0$, which has usually been interpreted as not useful for particle acceleration because a Lorentz transformation exists that makes electric field vanish. Such consideration, however, does not apply when there are large spatial variations of E or B or both. Indeed, our simulations show that both E and B vary on length scales that are comparable to the gyromotion of relativistic particles. We then proved that such field configurations can give rise to net acceleration of these particles, producing the energized population seen in Fig. 3.

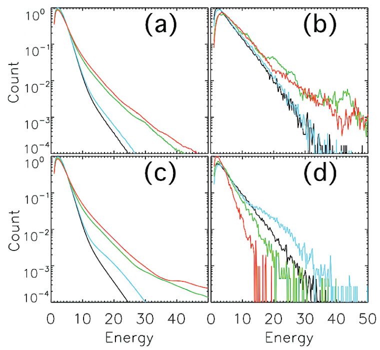

Fig. 3. Particle number distribution versus energy. (a) Whole computation domain; (b) sampling box at magnetic island; (c) total particles; (d) reconnection site. Black: initial particle energy distribution; Blue: end of linear instability stage; Green: tearing nonlinear stage; Red: final stage.

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